3D Viscous Inverse Method For Turbomachine Blades

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Abstract

Currently, state-of-the-art blade design systems employ the throughflow and possibly a 2D blade-to-blade inverse method in the initial design stage of the blade geometry. In many situations such as highly-loaded, low-aspect ratio blading, and high-pressure compressor blades, the quasi-3D method fails to design the proper blade profile. Consequently, many design cycles using full 3D analysis codes are used to modify the blade geometry until the desired flowfield is obtained. The focus of this project is to develop a full 3D and viscous inverse method for designing turbomachine blades. This method is developed to replace the blade-deviation correlations or the 2D blade-to-blade inverse method employed in the current design systems so that more efficient blading can be designed in a shorter time. This research program is divided into two primary tasks: development of the 3D inverse code and verification of the code using design test cases relevant to industry. This code was evaluated using design examples provided to us by several industry partners.

Development of the 3D viscous inverse code

The 3D inverse code in the inviscid limit was developed during the first year of the two-year project. The inviscid method developed earlier for 2D (Dang, 1995) was successfully extended to 3D. Our 3D inverse method uses blade pressure loading (ΔP) and thickness distributions as design parameters. Through discussions with designers at Allied Signal and Solar Turbines, it was confirmed that these design parameters were compatible with the design ideologies currently practiced as well as those envisioned for the future.

During the second year of the project viscous effects were implemented in the 3D inverse method. This 3D viscous inverse method uses wall functions for estimating shear stress along solid walls and thus maintains a slip boundary condition which is used in the inverse strategy. At present, a simple mixing length turbulence model has been used in the code, but the code can be readily modified to incorporate more sophisticated turbulence models.

Evaluation of the 3D viscous inverse code

The evaluation of the 3D inverse method was done in two stages. During the first year the method was evaluated in the inviscid limit. This was done by designing the first stage of a Solar Turbines compressor and a compressor stator with flow paths and design flow conditions

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Research sponsored by the U.S. Department of Energy under contract 95-01-SR037 with AGTSR, 386-2 College Avenue, Clemson, SC 29634-5181.

comparable to those given to us by Allied Signal. The 3D viscous inverse method was implemented in the second year and then evaluated by redesigning a compressor rotor built by Solar Turbines. The outcome of the evaluations is briefly described below.

Evaluation of the inviscid code

The graduate student working on this program went to Solar Turbines for an internship in the summer of 1996 and introduced to them this 3D inverse method. The inverse method was integrated with their existing design system and two Solar test cases were redesigned for demonstration of the inviscid version of the code. It was found that the inverse method could indeed design 3D blade profiles which resulted in matching the design parameters and overall flow features (including swirl distribution) obtained from Solar's throughflow solution. By automatically matching the optimized design parameters, the potential of this method in reducing the design cycle was demonstrated.

The other test case chosen for code evaluation was a compressor stator with highly 3D rotational-flow environment representative of a downstream blade row of a multistage machine. It had flow paths and design flow conditions comparable to those given to us by Allied Signal. The blade designed by the inverse was checked by the analysis mode and it was found that the solutions indeed matched well. This case demonstrated that our method does take into account the 3D effects of the flow field, which the existing design systems (the quasi-3D methods) neglect.

Evaluation of the viscous code

The graduate student working on this program went to Solar Turbines for another internship in the summer of 1997 for evaluation of the viscous inverse method. A transonic compressor rotor designed by Solar was used as a test case. First a consistency check was done with a commercial code commonly used in the industry (Dawes NS code), and it was found that the predictions with the viscous inverse code were quite satisfactory. Next the actual utility of the inverse code was demonstrated by redesigning the rotor with a modified loading. The blade surface pressure distributions were found to be better than the original and there was an improvement in the efficiency. It was thus demonstrated that the 3D viscous inverse method could be a very useful tool for improving existing designs.

This project has been extended to February 1998 because of increased interest from industries to further evaluate the code and demonstrate its design improvement capability. Thus the 3D viscous inverse code will be further evaluated by redesigning test cases of interest to Allied Signal and GE Power Systems.

Acknowledgments

This work is supported by the U.S. Department of Energy, under a two year contract with AGTSR. Daniel Fant is its contract monitor.

DEVELOPMENT OF ADVANCED 3D & VISCOUS AERODYNAMIC DESIGN METHOD FOR TURBOMACHINE COMPONENTS

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Research Area: Aerodynamic blade design

Objectives:

- Develop fully 3D Viscous Inverse method to design turbomachine blades
- Evaluate method with test cases from industry
- Integrate 3D inverse method into design systems currently used in industry

Benefits:

- Reduce design time
- Produce efficient blading

$\boxed{\text{Need to go from 2D to 3D}}$

- Existing inverse methods are 2D or quasi-3D

- 2D methods cannot correctly model
  $*$ rotational flows encountered in low aspect ratio blades and
  $*$ 3D shock structure in tip region of transonic blades

Consequence $\longrightarrow$ design is an iterative process

- Need for a fully 3D inverse method

Methodology

Current Procedure

Throughflow method $\longrightarrow$ inlet & outlet flow conditions for each blade row

Blade Geometry $\longrightarrow$ superimpose thickness to camber

- Thickness distribution (NACA, c4, T4, ..)
- ⋆ Camber shape: Circular Arc, parabolic, polynomial
- Include incidence and deviation angle corrections

Our method

- ⋆ Choice of camber surface replaced by blade pressure loading distribution (Δ P)

Governing Equations

Use existing robust time-marching schemes to solve equations of motion (e.g. JST finite-volume scheme)

$$\frac{d\mathbf{U}}{dt}+\frac{1}{Vol}\int_{cell}(\mathbf{E}-\mathbf{E_v})d\mathbf{A_z}+(\mathbf{F}-\mathbf{F_v})d\mathbf{A_r}+(\mathbf{G}-\mathbf{G_v})d\mathbf{A}_\theta=\mathbf{H}$$

where the conservative variable vector $\mathbf{U}$ is defined as

$$\mathbf{U}\equiv[\rho,\rho V_z,\rho V_r,\rho r V_\theta,e_t]^T$$

the inviscid-flux vectors ($\mathbf{E}$,$\mathbf{F}$,$\mathbf{G}$) are

$$\mathbf{E}\equiv[\rho V_z,(\rho V_z^2+p),\rho V_z V_r,\rho V_z r V_\theta,(e_t+p)V_z]^T$$

$$\mathbf{F}\equiv[\rho V_r,\rho V_r V_z,(\rho V_r^2+p),\rho V_r r V_\theta,(e_t+p)V_r]^T$$

$$\mathbf{G}\equiv[\rho V_\theta,\rho V_\theta V_z,\rho V_\theta V_r,r(\rho V_\theta^2+p),(e_t+p)V_\theta]^T$$

the viscous-flux vectors ($\mathbf{E_v}$,$\mathbf{F_v}$,$\mathbf{G_v}$) are

$$\mathbf{E_v} \equiv [0, \tau_{zz}, \tau_{zr}, \tau_{z\theta}, 0]^T$$
$$\mathbf{F_v} \equiv [0, \tau_{rz}, \tau_{rr}, \tau_{r\theta}, 0]^T$$
$$\mathbf{G_v} \equiv [0, \tau_{\theta z}, \tau_{\theta\theta}, \tau_{\theta r}, 0]^T$$

and $\mathbf{H}$ is the source term

$$\mathbf{H} \equiv \left[0, 0, \frac{\rho V_\theta^2 + p}{r} - \tau_{\theta\theta}, 0, 0\right]^T$$

Blade surface definition:

$$\alpha^{\pm} \equiv \theta - (f \pm \frac{T}{2}) = n\frac{2\pi}{B}$$

Camber surface generator { from flow tangency }:

$$< \vec{V} >_{bl} \cdot \nabla f = \left(\frac{< V_\theta >_{bl}}{r} - \omega\right) - \frac{1}{4}\Delta_{bl}(\vec{V}) \cdot \nabla T$$

Boundary Conditions

Permeable boundaries at blade surface:

Jump conditions in pressure **p** imposed at blade surface

$$p^{\pm} = < p >_{bl} \pm \frac{1}{2} \Delta p$$

where Δp is related to the overall change in mass averaged angular momentum across the blade row for a given streamtube

$$\int r \Delta p dA_{\theta} = \dot{m}[(r\bar{V}_{\theta})_{TE} - (r\bar{V}_{\theta})_{LE}]$$

Slip boundary conditions at solid surfaces even for viscous flow by use of wall functions

Viscous Effects

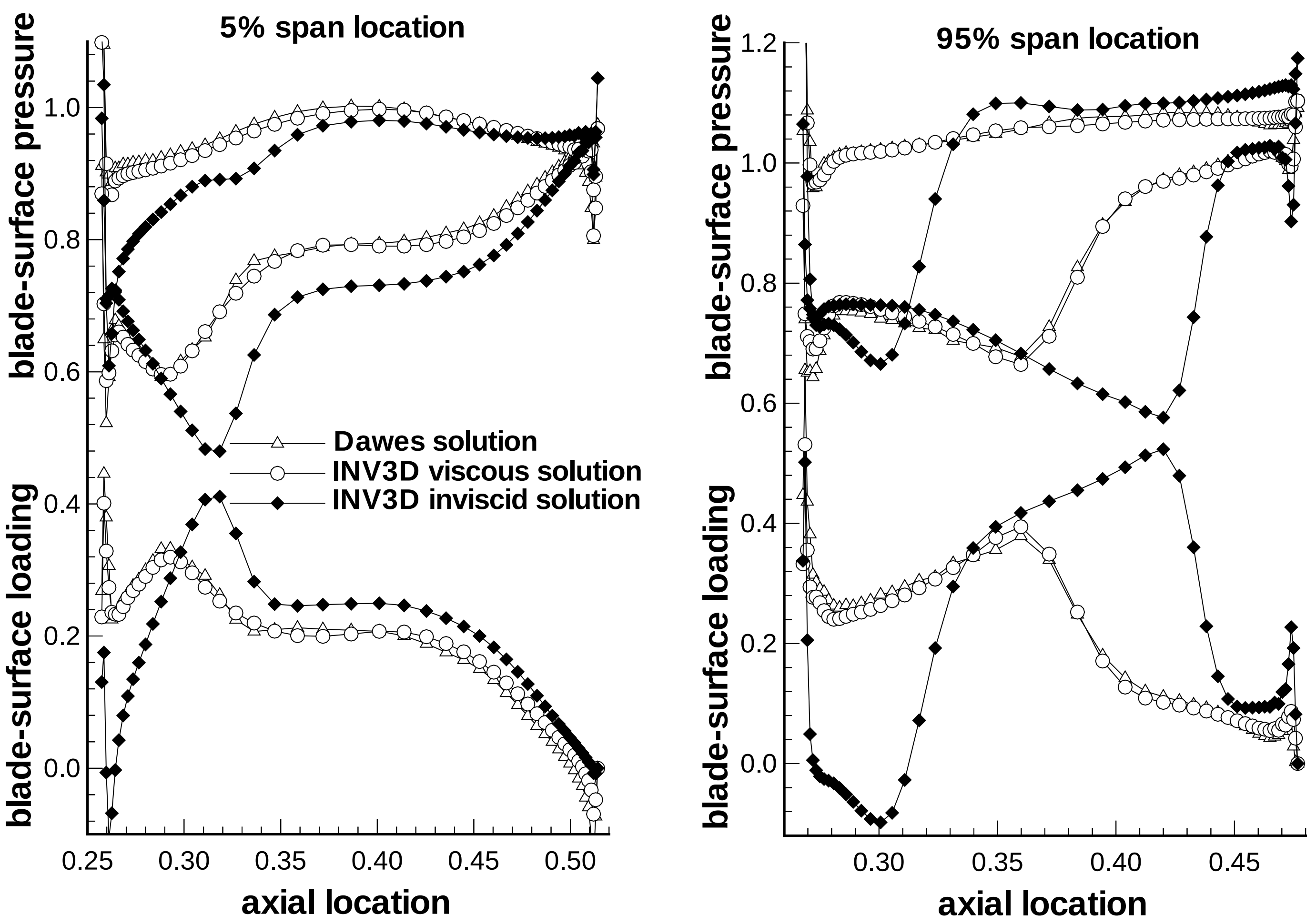
- Estimate wall shear stress using wall function.
- Simple mixing length turbulence model away from wall.
- Slip boundary condition along solid surfaces.

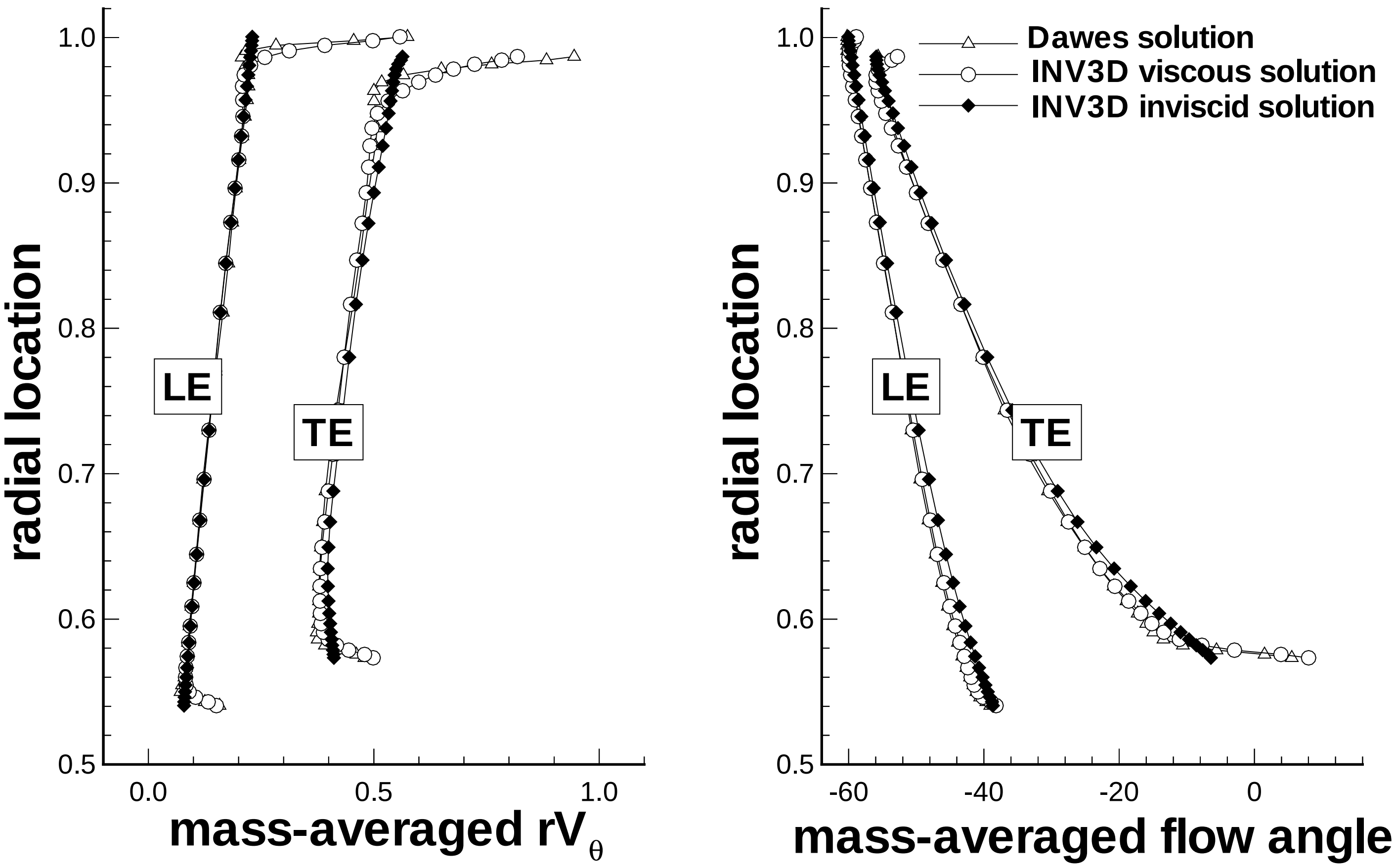
Conclusions

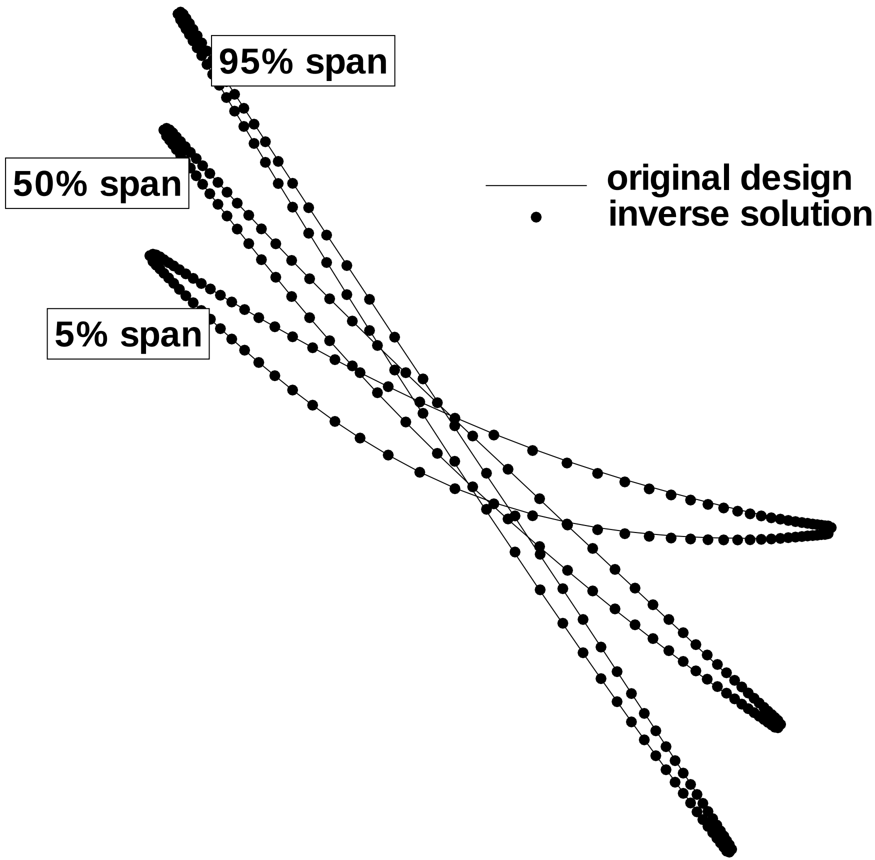
- 3D viscous inverse method development near completion
- Our inverse method was evaluated with test cases from **Solar Turbines** and **AlliedSignal**
- Practicality of viscous inverse method demonstrated for improving existing design

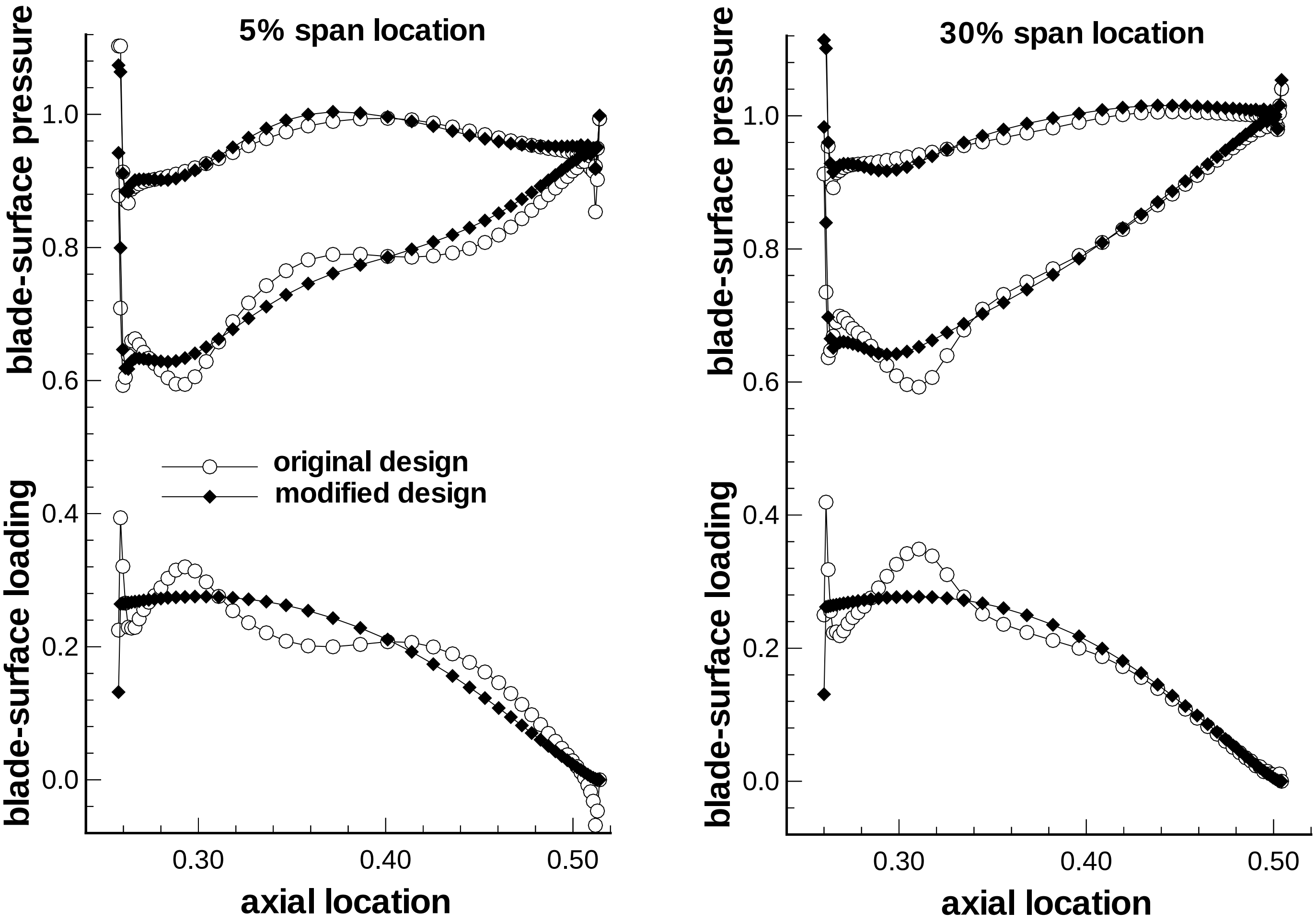
Future Work

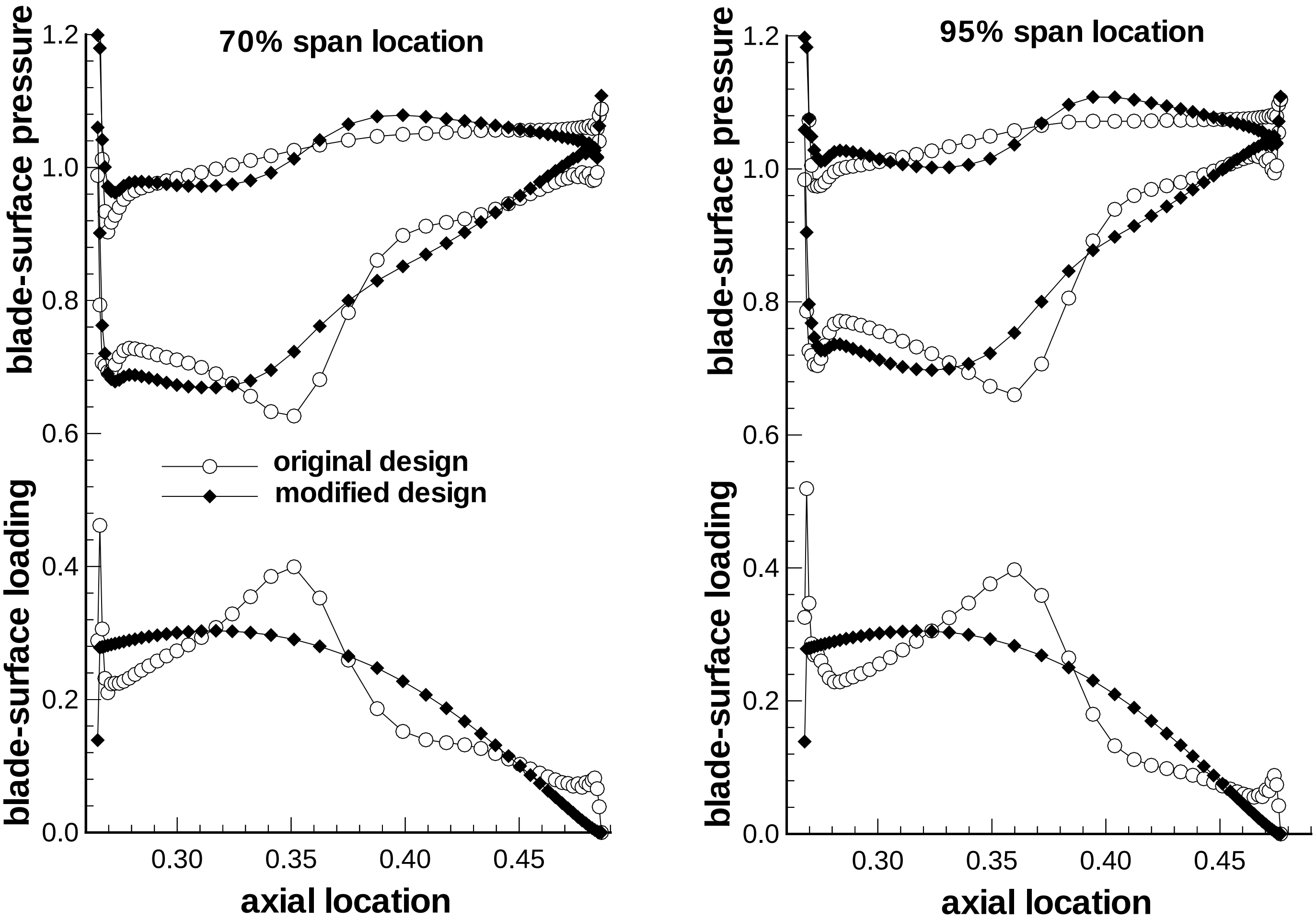
- Further evaluate method by designing test cases of interest to Allied Signal and G. E.


5% span location
95% span location
blade-surface pressure
blade-surface loading
axial location
Dawes solution
INV3D viscous solution
INV3D inviscid solution
0.25
0.30
0.35
0.40
0.45
0.50
1.2
1.0
0.8
0.6
0.4
0.2
0.0

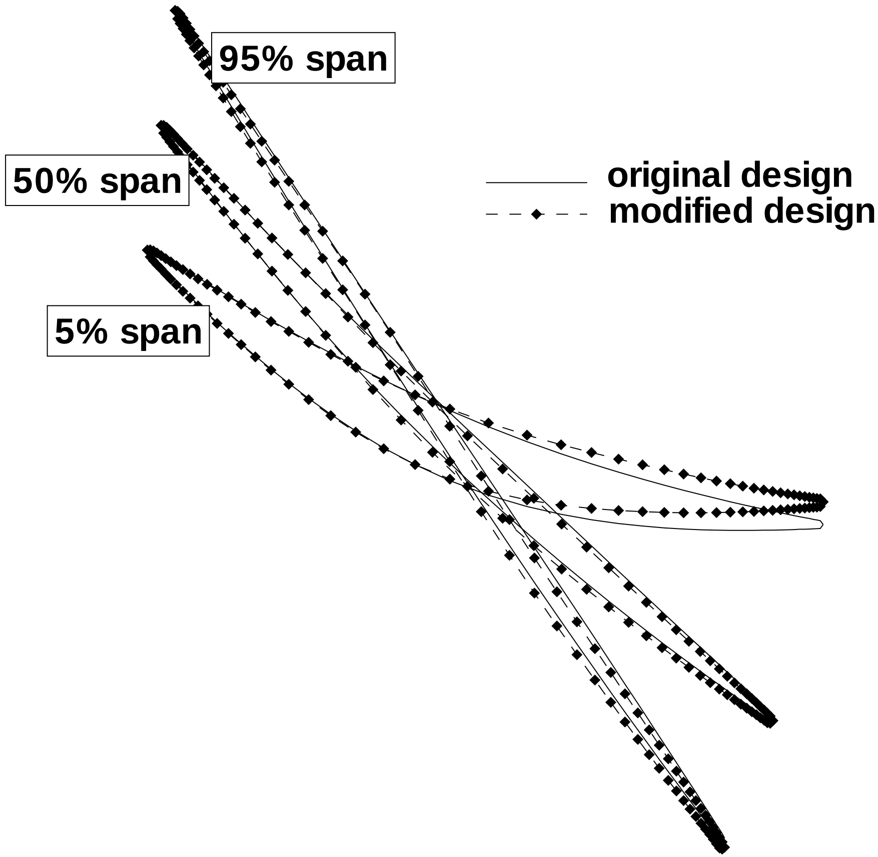

radial location
1.0
0.9
0.8
0.7
0.6
0.5
0.0
0.5
1.0
mass-averaged rV_θ
LE
TE
radial location
-60
-40
-20
0
mass-averaged flow angle
LE
TE
Dawes solution
INV3D viscous solution
INV3D inviscid solution

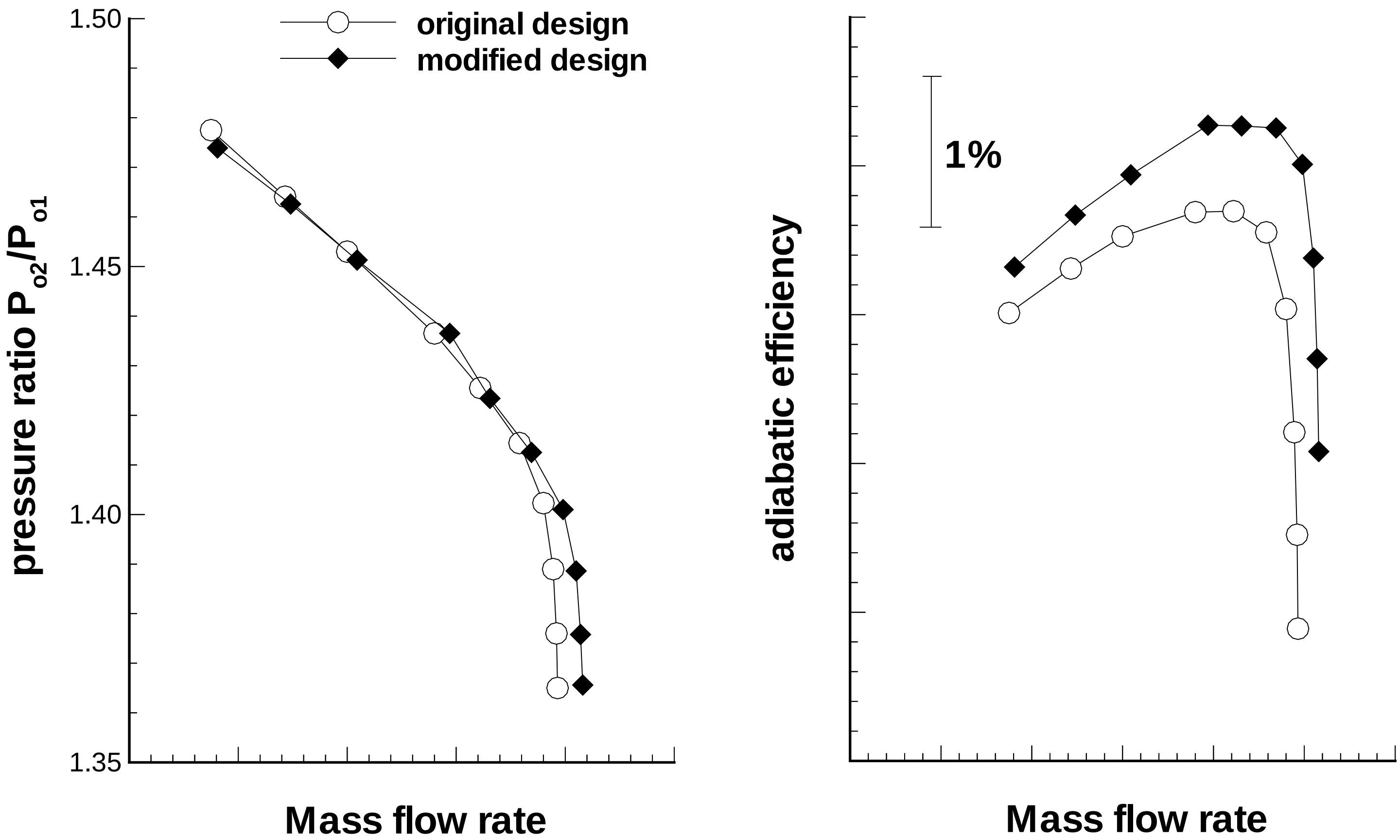

95% span
50% span
5% span
original design
inverse solution


5% span location
30% span location
blade-surface pressure
blade-surface loading
original design
modified design
axial location
0.0
0.2
0.4
0.6
0.8
1.0
0.30
0.40
0.50

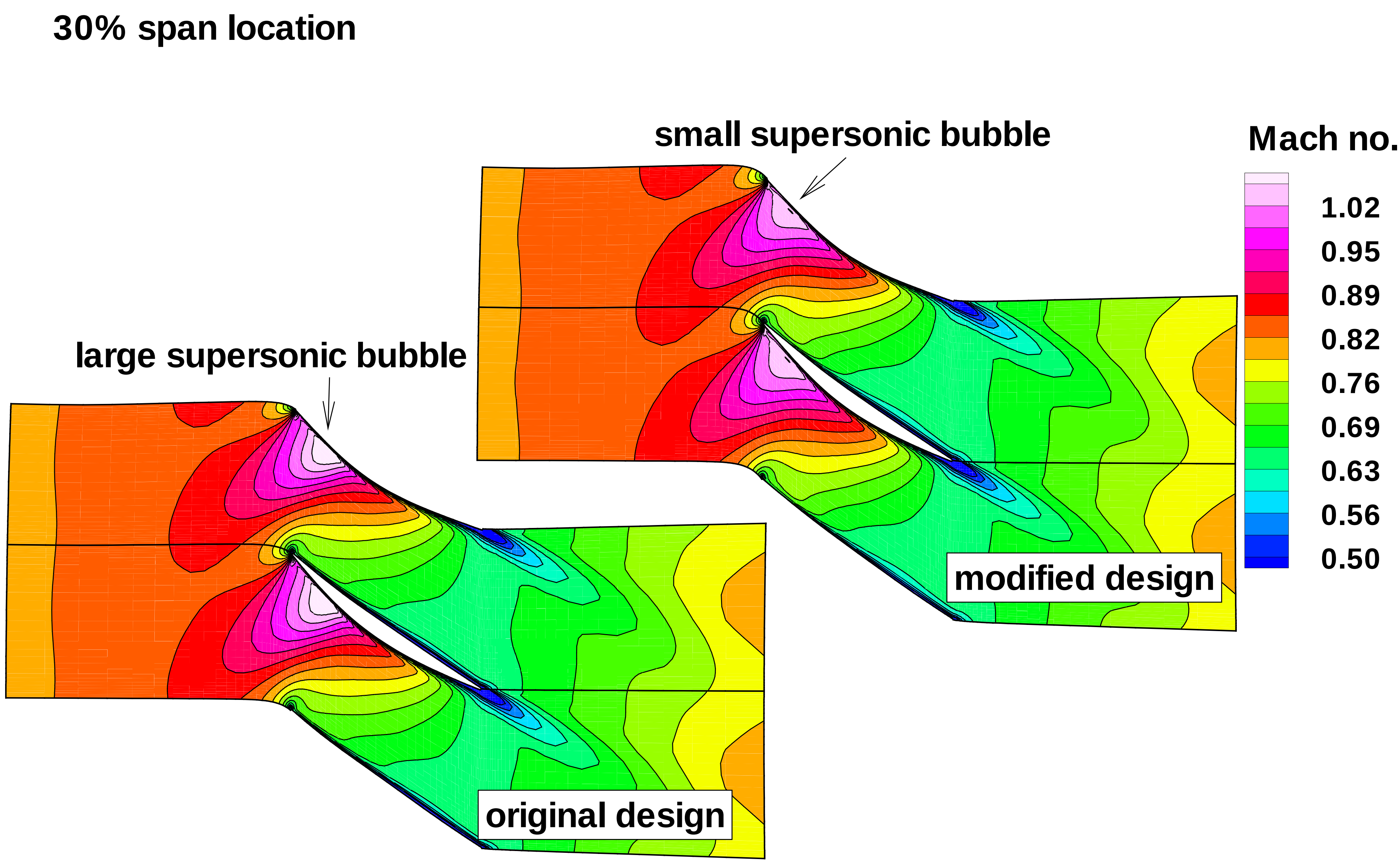


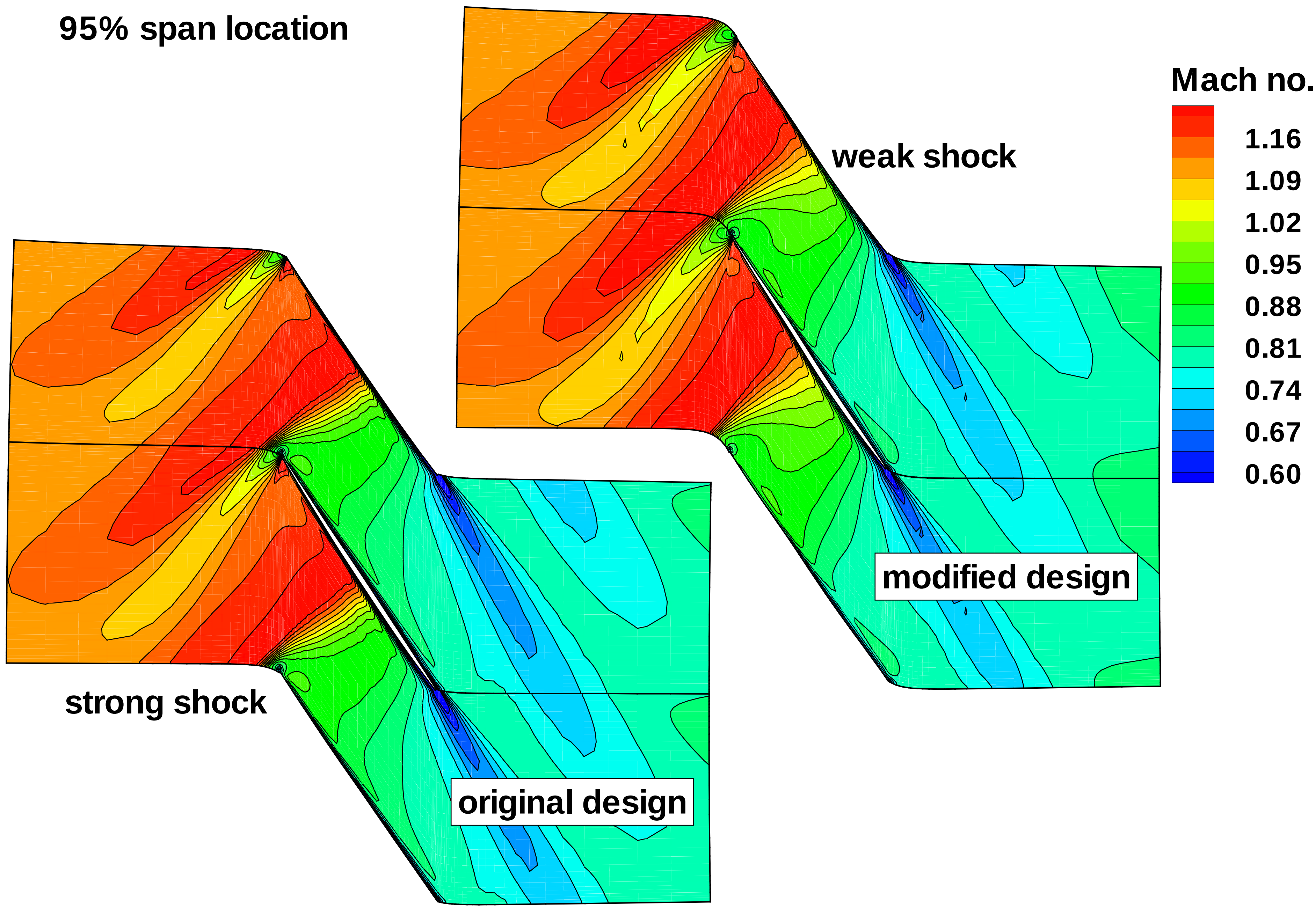
70% span location
95% span location
blade-surface pressure
blade-surface loading
original design
modified design
axial location
1.2
1.0
0.8
0.6
0.4
0.2
0.0
0.30
0.35
0.40
0.45

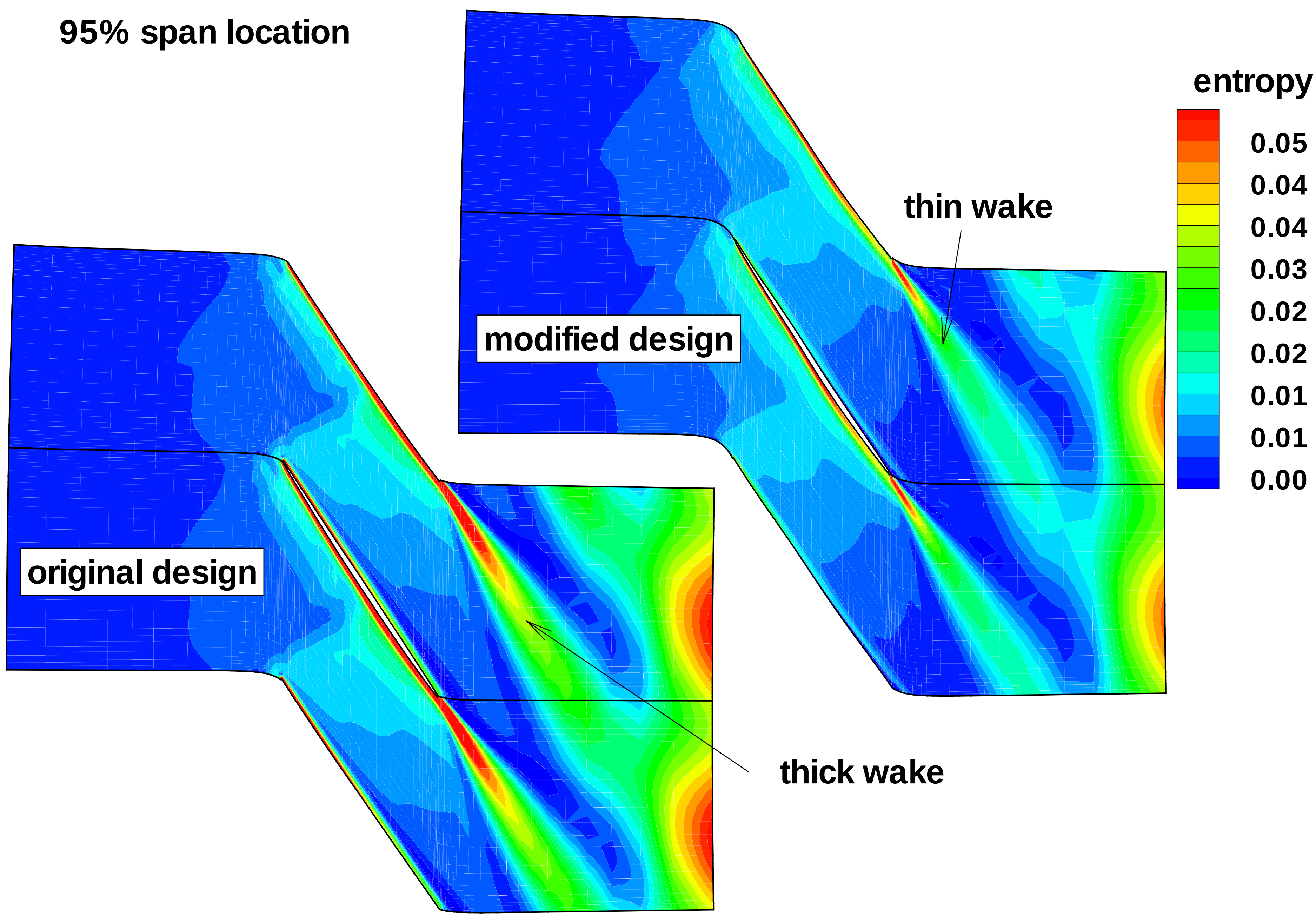

95% span
50% span
5% span
original design
modified design

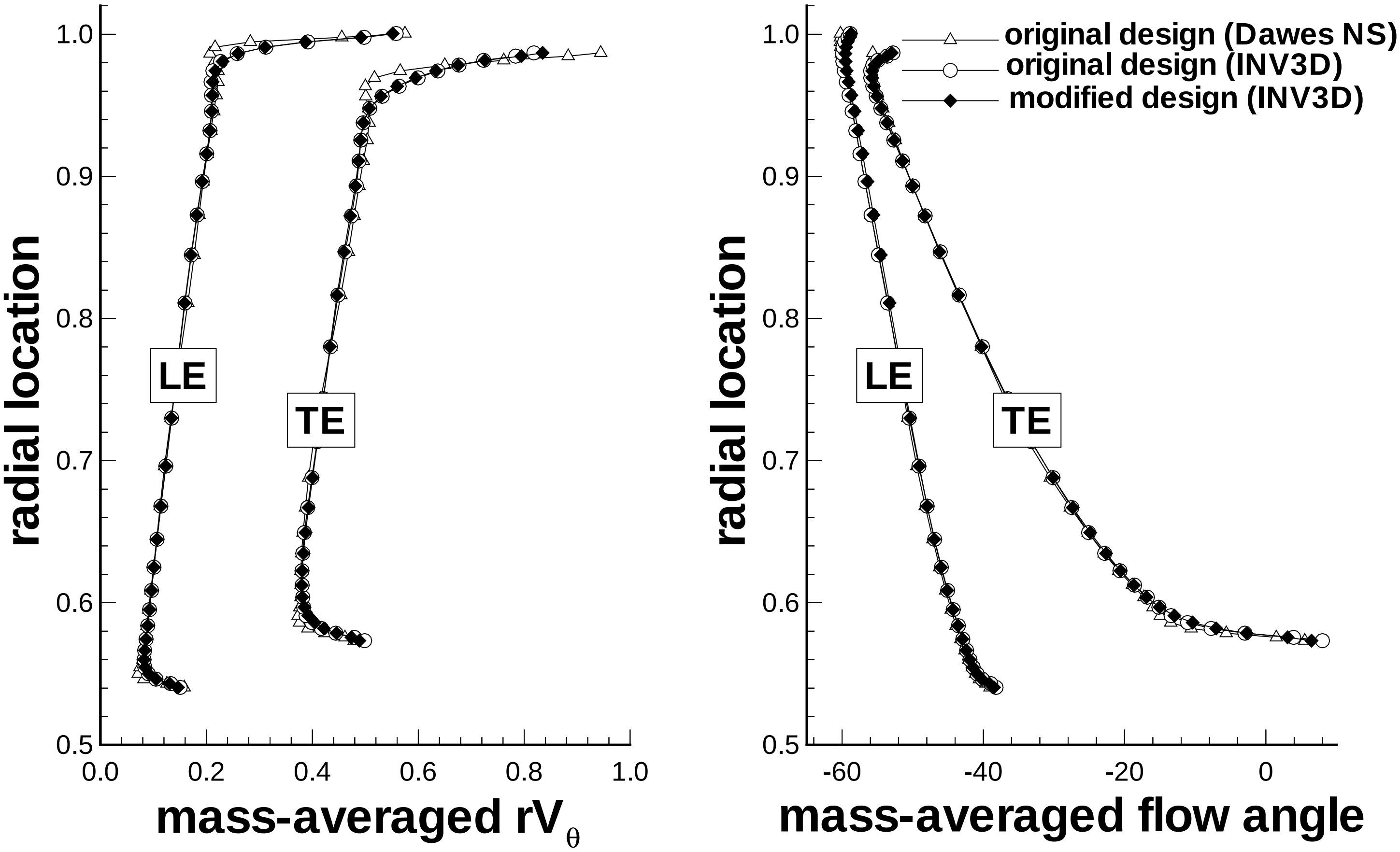


original design
modified design
1.50
1.45
1.40
1.35
pressure ratio P_{o2}/P_{o1}
Mass flow rate
1%
adiabatic efficiency
Mass flow rate


30% span location
small supersonic bubble
large supersonic bubble
Mach no.
1.02
0.95
0.89
0.82
0.76
0.69
0.63
0.56
0.50
modified design
original design


95% span location
weak shock
Mach no.
1.16
1.09
1.02
0.95
0.88
0.81
0.74
0.67
0.60
modified design
strong shock
original design


95% span location
modified design
original design
thin wake
thick wake
entropy
0.05
0.04
0.04
0.03
0.02
0.02
0.01
0.01
0.00



radial location
mass-averaged rV$_\theta$
LE
TE
1.0
0.9
0.8
0.7
0.6
0.5
0.0
0.2
0.4
0.6
0.8
1.0
radial location
mass-averaged flow angle
original design (Dawes NS)
original design (INV3D)
modified design (INV3D)
-60
-40
-20
0